

INFORMATION SCIENCES EXPERIMENT SYSTEM

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Abstract

The rapid expansion of remote sensing capability over the last two decades will take another major leap forward with the advent of the Earth Observing System (Eos). An approach is presented in this paper that will permit experiments and demonstrations in onboard information extraction. The approach is a non-intrusive, eavesdropping mode in which a small amount of spacecraft "real estate" is allocated to an onboard computation resource. This paper discusses how such an approach allows the evaluation of advanced technology in the space environment, advanced techniques in information extraction for both Earth science and information science studies, direct to user data products, and real-time response to events, all without affecting other onboard instrumentation.

Introduction

The United States Space Program is about to undertake its most ambitious effort yet in remote sensing of the Earth's environment. The centerpiece of this activity is the Earth Observing System (Eos) which is a joint endeavor of NASA's Space Station Program and NASA's Office of Space Science and Applications. As the Space Station "Freedom" is a major step forward for the United States in space infrastructure, the Eos will be a major step forward for the United States in environmental monitoring.

Since the Space Station Constellation (Core Station and Polar Platform) is planned to be of very long life and use, it is important to ensure that its capability has provision for growth. Capability growth can come from a variety of sources, not the least of which is the application of new technologies and techniques as time goes on. Unfortunately, space flight systems rarely have provision for excess capacity (data, weight, power, etc.) to permit accommodation of additional functions.

Without the opportunity to evaluate potential technologies and techniques in space, the necessary "confidence-building" to convince program managers and project engineers to use new technologies or techniques is lacking. A "Catch 22" ensues in which new approaches are proposed to be tried in the space environment, but are rejected for use because they don't have the requisite space flight experience. New technology is rarely used because it is not mature; and by the time it gets mature, it is no longer new. On the other hand, the need for more rapid application of new technologies is never more apparent than in the Eos. The Eos is in many respects the continuation of a long line of remote-sensing systems which have provided far more data than can sensibly be absorbed. The historical "data glut problem" is very much in evidence in the Eos. One instrument, called the High Resolution Imaging Spectrometer (HIRIS), has an anticipated internal data rate nearly twice the capacity of the data relay satellites sent to the ground.

This paper provides some background on the Eos and discusses the "data glut problem" particularly concerning Eos. A systems approach is presented, allied with Eos objectives, that addresses some important issues related to space remote-sensing systems capability. This system, called the Information Sciences Experiment System (ISES) has as its objective onboard information extraction for use either directly to the ground or on-board. This paper also shows how the Eos offers a unique opportunity to apply this new approach, and how the ISES can effectively address (1) the insertion and evaluation of new technology and techniques for space use without adversely impacting overall system performance, (2) the "data glut problem", (3) the increase of the onboard use of assets, (4) the use of real-time response to events, and (5) the provision of direct-to-user data products. Finally, some comments related to the applicability of the ISES approach to the Core Space Station are made.

The Earth Observing System (Eos)

The Eos is, in part, an outgrowth of early Space Station Program thinking, where both equatorial and polar orbiting spacecraft were contemplated to be derived from the same flight hardware. The polar orbit was important to supplement the near equatorial orbit of the manned space station supporting science applications. Only through high orbital inclination can complete global coverage be obtained from a low-Earth orbit. Independently, but contemporaneously, NASA's Office of Space Science and Applications had begun studies to determine what the next step should be in remote sensing of the environment. The result of these studies pointed to a need to look at the Earth from a unified perspective recognizing the interdependence of the processes shaping our environment.

The details of the scientific rationale for what first became "System Z" and then the Eos can be found in Reference 1, and will not be discussed here. The current state of the Eos concept is, in fact, one with a wide variety of remote sensors that look up, look down, back, and sideways, detecting radiation from very high energies to very long wavelength phenomena. Magnetometers are included as are electric field meters. Environmental targets include crops, water resources, atmospheric chemistry, ice, oceanic processes, lightning, air glow, and so on. Again, the interested reader is directed to Reference 1. What is of interest are the results of the Science and Mission Requirements Working Group (SM&RWG), which give the requirements that must be met to realize a practical system to enable a unified approach to Earth studies. Of the five recommendations, two specifically address the data and information aspects in an implementation strategy (Reference 1).

Within the current Eos concept is an extensive ground data network with considerable resources and capabilities to receive, preprocess, store, distribute, and exchange data sets. A schematic of this concept is illustrated in Figure 1 (and abstracted from Reference 2), which shows a very simplified ground and flight data system. When one looks for the equivalent access to data systems resources in the flight element, one is struck by its relative absence.

The lack of onboard computational capability is remarkable when it is realized that of the three types of experimenters participating in Eos, one is "Multidisciplinary Investigators." The Eos, proposed as enabling a unified approach to Earth studies, has no real provision for addressing that goal on the spaceflight vehicle itself. The reason for this situation lies in the dichotomy of the Eos and the spacecraft on which it flies. The Eos is a system of remote-sensing instruments and outlines

an approach to Earth studies that is hosted on a spacecraft developed as part of the Space Station Program. Eos and the polar platform on which it flies are separate and distinct.

The Space Station Program as the host generally supplies certain basic services to its users and customers such as power, thermal rejection, spacecraft ephemeris, time code, communication, and other housekeeping information. Because of the extreme diversity of potential users, the complexity and attendant cost of providing general computational services was not deemed to be protected. If a user has a need for special services, it is that user's responsibility to provide those services and bear the cost.

On-Orbit Data Processing and Eos

NASA has been well aware of the problem posed by remote sensors, particularly high volume/high data rate systems. The earliest weather satellites and Earth resources satellites were already creating considerable archives of data in the late 1960's and early 1970's. A typical early example was the Multispectral Scanner (MSS) of the Landsat spacecraft, which was a four-band imager. The data rate for this instrument was 15 Mbits/second. At that time, a typical 1,200-foot reel of 800 bpi magnetic tape held about 108 bits. Archiving data from the MSS would fill a reel of such tape every 7 seconds.

The situation just described has remained in an uneasy equilibrium in the ensuing years. New data processing and data storage technology have come on the scene, to be pressed even harder by new high volume, high data rate remote sensors. A somewhat arbitrary but still reasonably accurate illustration of the historical trends is shown in Figure 2. The growth in Data Processing Technology and Data Storage Technology is compared to demands from spaceborne remote sensors. It is arguable that even with the very impressive strides made in data systems technology, sensor systems continue to overwhelm the systems required to work with them.

Included in the figure is a point to represent the Eos. Most of the Eos data is generated from a handful of instruments such as HIRIS, Moderate Resolution Imaging Spectrometer (MODIS), and Synthetic Aperture Radar (SAR). It is also true that these are very powerful instruments with a phenomenal number of spectral channels or ground resolution. It is hard to imagine any further development on these sensor concepts. However, the upper limit is nowhere near reaching its fullest development.

A rough calculation of the ultimate data rate and data volume potential shows something of the top end. Assuming a Landsat or Eos orbital altitude of 800 km with a ground track speed of 6.5 km/second, and an imager with a 1-m diameter mirror operating at 1 micrometer wavelength, one can arrive at the possible data rate. For assurance of complete access to any point on the Earth, the field of coverage would be 1,700 km per orbit. A 1-m mirror at 1 micrometer has a diffraction limit at 800 km of about 1 m, assuming there are two-to-one overlapped ground sampling 2×10^{10} samples per second per spectral channel. For 10-bit encoding and for the 100 or so channels of an Eos MODIS instrument, a final figure of 2×10^{13} bps is produced.

It should also be noted that geostationary platforms would offer some improvement, but not much. Assume that the 1-micrometer resolution is held at the 40,000-km range of a geostationary platform, and assume that one complete scan every hour would still be close to 10^{11} bits/second. As mentioned earlier, NASA was and has been well aware of the developing "data glut problem" and

has moved to address it. The result was the NASA End-to-End Data Management System (NEEDS) program which started in the mid 1970's. The NEEDS Program had as an objective of 1,000 to 1 improvement in the rate of conversion of data to information (Reference 3). The NEEDS Program had various elements, but was divided into a ground element and a flight element. It is fair to say that the objective of improving the information extraction rate by three orders of magnitude was not achieved, and that the greatest disappointment in the NEEDS was in the flight element. No hardware developed for the flight element has been included on a NASA spacecraft. The irony is that some rather capable hardware was developed for the flight element. Flight upgradable hardware was produced which was fast enough to do step-wise linear corrections to sensor nonlinearities, provide gain and offset correction, and do real-time cloud editing. Geometric resampling was also close to being realized at real-time rates.

The reason that the NEEDS flight hardware was never flown can be ascribed to a variety of reasons, but three are of interest here. First, the objectives of moving very simple processing functions to orbit were not really cost effective. Second, the hardware was demonstrated on the ground with no "confidence building" space flight experiment to demonstrate its power. Third, capabilities that the flight element demonstrated did address significant data system problems. However, scientists and other end users of the remote-sensing data were looking for diverse end products with ultimate accuracy generated by complex algorithms yet to be determined. With this set of difficulties, the flight element of the NEEDS Program foundered. Yet it is intuitive that there is much that can and should be done on orbit. Some of the fundamental obstacles to both flight and ground elements in the NEEDS Program were in fact our lack of understanding of the physical relationships between what can be sensed and what we are trying to derive. There was no algorithm engraved in stone, which when applied to multispectral sensor data, would tell us how much corn was being grown on a particular patch of soil in Kansas.

The Eos: An Opportunity Regained

In light of what has been discussed previously, the Eos concept now should be considered. The Eos is most radical in its departure from prior U.S. Earth observation spacecraft in that it has been, from its inception, aimed at broad spectrum scientific objectives and the interplay among them. The Eos recognizes that major Earth processes interact with one another. In fact even in the past, it was recognized that observations were contaminated, obscured, or significantly impacted by outside effects: crop signatures blurred and modified by atmospheric effects, Lidar measurements sensitive to water vapor aerosols, sediments affecting chlorophyll signatures, and so forth.

To make significant statements about major Earth processes, it may be much more beneficial to reasonably define the multi-input, multi-output process than to continue to develop and fly more and more complex sensor systems, when the problem is in the physical understanding and not the hardware. Thus, models including good if not perfect algorithms may be perfectly adequate for Eos objectives.

ISES: The Information Sciences Experiment System

A concept has been proposed called ISES, which can avoid many of the problems encountered in the NEEDS Program, and at the same time address some very major issues of onboard information

extraction. The key to the ISES concept is the commitment by the flight project of some "real estate" on the spacecraft: power, weight, access to the data system, and a time slot in the communications stream.

Basically, what is proposed is a "black box" attached to the spacecraft data bus or LAN. To the spacecraft the "black box" appears to be just another remote sensor requiring power, heat rejection, interfaces, adding weight, and requiring time on the data management and communication system. In reality, the "black box" is a programmable computational resource which eavesdrops on the data network, taking data and producing selectable science information back on the data network. An added element to the ISES is a proposed laser communication experiment for direct-link-to-ground experiments. The incorporation of the ISES into the Eos flight is shown in figure 3, where it can be seen that the "black box" simply interfaces into the Eos platform data network, like other instruments and, like them, communicates to the ground through the two radio frequency (RF) links. (The two RF links are: the primary Telemetry Data Relay Satellite (TDRS) and, on a non-interference basis, a proposed NOAA/NASA, 100-MBit/second, direct-to-user RF link.)

A system can therefore be instituted characterized by, among others, the following six items:

- (1) Conducting onboard information extraction experiments and demonstrations.
- (2) Not modifying investigators' data.
- (3) Avoiding "mission critical" constraints.
- (4) Making real-time event response possible.
- (5) Defining flight experience as "confidence building."
- (6) Identifying desirable technology areas.

Item (1) is made possible by eavesdropping on instrument data as it either passes around a LAN or is placed on the data bus. With the ability of picking up data from a variety of instruments as they are being taken comes the possibility of executing information extraction experiments in the "black box." Since the "black box" is a computational resource, algorithms can be run (which according to Eos provisions must be freely shared) to extract whatever end product is desired. More particularly, data retrieval that requires inputs from other data sets ("sensor fusion") can be executed. High data rate or low data rate experiments can be run on selected subsets of data by "frame snatchers." Thus, significant experiments can be performed on a modest size computational resource with modest data storage capability. Once finished with the experiment, the results are then prepared for transmission and presented back to the Eos data system. It is anticipated that information extraction experiments will be run in both the areas of Earth resources and information sciences and that those experiments will be defined by a science team representing both groups.

Item (2) is important, since as has been discussed previously, one of the major concerns with onboard information extraction has been the principal investigator's objection to irreversible modification of data when the ultimate algorithms are as yet undiscovered. The ISES avoids this by running in parallel with the actual investigator's experiment by copying the data into its memory, and by not handling the data in any way. Consequently, this approach allows timely comparisons of investigator data with whatever quick-look data or other early processing that is planned.

Item (3) answers the question of adding advanced technology to flight systems which might be considered immature concerning reliability. Failure of some or all of ISES does not result in the

failure of anything except experiments ISES hosts. Treating the computational resource as a payload relieves some of the reliability and quality assurance rigors, since payloads would not be considered "mission critical."

Item (4) refers to the possibility of responding to events that may be observable from Eos in real-time. Data from experiments observing weather phenomena, for example, could be monitored continuously for suspicious features by ISES, and if something is identified, a priority communication could be executed or high-resolution sensors commanded to examine the feature more closely.

Item (5) is reasonably self-evident. Nothing develops confidence in space flight hardware than actual demonstration and use in space. The more flight time the hardware logs, and the more routine use it gets, the more actual experimental data base is developed and the more comfortable mission managers become in supporting future applications.

Item (6) is a side benefit from trying technology that shows promise and points to areas that could benefit from further development. Special-purpose hardware and special functions being performed could yield results that are extremely useful, but far from being fully exploited.

Whereas the approach of flying the onboard processing system as a payload rather than part of the spacecraft support hardware obviates many objections, ISES is then left with justifying itself in its own arena. The most serious obstacle to ISES in a head-to-head competition with other potential payloads is the lack of a developed advocacy in the science community. Such a lack is something like the "chicken and egg" dilemma: Without prior access to onboard, real-time computational capability, there is no opportunity for experiments or participation. Without opportunity, advocacy community cannot be developed; without advocacy community, there can be no onboard computation. Since ISES has elected the payload approach, its justification must survive competition against the other potential payloads. Thus, one major element in defining ISES is the development of science and user requirements for peer review and program cost-benefit assessment.

A science team made up of two sub-groups, an Earth sciences team and an information sciences team, develops ISES requirements. Given the nature of Eos, the information sciences team must develop its experiments and demonstrations in and around those developed by the Earth sciences team.

At this point, it is worthwhile noting that the science teams must develop a set of requirements in the form of experiments and demonstrations. The ISES concept distinguishes among three classes of activities: (1) experiments, where there are competing concepts, algorithms, theories, etc.; (2) demonstrations, where a leading approach, algorithm, etc., has been identified, tested, and evaluated; and (3) operational systems, where the relevant demonstration has been done, effectiveness and utility proven. ISES has the objective of addressing elements (1) and (2).

A second major activity in the ISES approach is the definition and development of the physical ISES flight and ground system, including hardware and software, etc. The science requirements, converted to quantitative experiment scenarios, with algorithms, are mapped against potential hardware options. An optimization process must maximize the science return (with prioritized experiments) within the expected allocation of platform resources (power, weight, volume, heat rejection, etc.) Thus, the ISES concept is predicated on technology driven by science rather than technology for technology's sake.

Regarding other payloads that might include internal information extraction or data processing, ISES is neutral. Whatever other instruments do to their data, whatever information extraction the Principal Investigator and his Science Team will allow as "in-line" processing, simplifies the task for ISES, so long as there is available knowledge of final output. ISES operates in parallel with other instruments, and its structural relationship to internal instrument processing can be illustrated as shown in figure 4. ISES deals with instrument data as a constraint, but one which is a legitimate consequence of the ISES eavesdropping, non-intrusive, approach.

Direct-to-Users

An aspect of the ISES concept which has considerable potential for magnifying both the range of experiments and the extent of participation is direct-to-user information transmission. The baseline communication method for ISES is through the Eos space-to-ground link (the Telemetry Data Relay Satellite System (TDRSS)). After performing the information extraction experiment or demonstration, ISES typically would wait its turn and when appropriate, feed its information into the LAN, which in turn, would send the data to the platform data and communication package for transmission through TDRSS to the ground.

Two other paths to ground, including "in-the-field" users exist. First is what was originally proposed to be NOAA's direct broadcast communication link. The second path is part of the ISES concept and is a proposed laser communication demonstration.

The NOAA link, as originally proposed, was composed of four elements: A VHF or UHF data collection transponder, a VHF Automatic Picture Transmission (APT) subsystem, an S-Band High Resolution Picture Transmission (HRPT) subsystem, and a 100 Mbit/sec Landsat-like subsystem. Scattered throughout the world, there are about 800 APT-compatible stations, 76 HRPT-compatible stations, plus a few Landsat-compatible stations (Reference 4).

It is likely that NOAA instruments or communications packages will NOT be on the first Eos platform, and consequently, discussions have taken place for alternative suppliers of the direct-to-users link. One option is for ISES to support the formatting of data for the physical RF system, including the generation of substitutes for the original NOAA data and the ISES experiment results.

The HRPT stations are of considerable interest, since they represent digital data receiving capability. The HRPT format consists essentially of a 0.665-Mbit/sec data stream that is derived from the AVHRR joined to atmospheric sounder, limb scanner, and radiation monitor data. A digital data format similar to that in HRPT can be considered quantitative as opposed to the qualitative data from the analog APT system. With all the necessary RF receiving station hardware, antennas, preamplifiers, bit synchronizers, etc., already established and ready, using such ground stations offers many more potential experiments for ISES to perform, particularly regarding contemporaneous and location specific applications. It is possible to imagine universities, local governments, or perhaps, companies participating much more readily in the global environmental studies or applications, if their involvement is direct. The ISES concept offers a flexible approach to tailoring the powerful and broad capabilities of the sensing systems on Eos to the specific concerns under the spacecraft's flight path.

Basically, the HRPT output is just a digital data stream which happens to be formatted from line scan imagery data with atmospheric and radiation environment data appended in each data

frame. The content in the frame in the Eos context could be anything that the experimenter wants, abstracted from any of the various sensor systems on Eos. Some simple adaptation of the current HRPT systems may be necessary to avoid interference with the NOAA TIROS satellite frequency at S-Band. Users may have to purchase new crystals, etc. and software would have to be modified. Nevertheless, the resulting systems would be an inexpensive way to receive data from the most powerful remote sensing system ever flown and to widen participation in a dramatic way.

An example of applying new technology to the space environment is the laser communication experiment in the ISES proposal. This experiment represents a demonstration of the ISES approach to evaluating new technology such as semiconductor diode lasers in a space-to-ground link. As currently envisioned, the laser communication experiment will be split into two major portions: the first portion is a moderate data rate, direct-to-earth science-field users objective in which the ability to establish enough bi-direction communication to fill an empty personal computer fixed disk in one pass of the polar platform is demonstrated. Since this represents about 15 minutes from horizon-to-horizon, a rate of about 10 bits/second is enough, which is a low rate. The second portion of the experiment will support information sciences with an objective of gigabit rate links near the poles. The very difficult job of acquisition and tracking is greatly ameliorated by the stated accuracies to be provided in the polar platform ephemeris. (The position is known to be better than plus or minus 10 m.) The demonstration of bi-directional space-to-ground optical communication has many desirable features and stands as an already defined experiment in ISES (fig. 5).

Relation to the Core Space Station Freedom

At this point, it is worth commenting on the application of the ISES concept to the Core Space Station Freedom, that will be in a low-inclination orbit. The Eos will be in a high-inclination polar orbit, placed there by an expendable launch vehicle and it will be very likely that whatever hardware placed there will be capable of easy change out. The Eos ISES will rely very heavily on a fixed hardware environment and a versatile software environment to support simulations and emulations. The Core Space Station Freedom, on the other hand, represents the permanent manned presence. The Core Station is, by design, maintainable, evolvable, and repairable, lending itself to supporting an ISES concept with a far more flexible hardware environment. Thus, experiments and evaluations of novel hardware become a reality. Items such as optical processors, neural nets, and other hardware treated as coprocessors or firmware are possible. Moreover, the Core Space Station is itself the subject of study as a complex, somewhat flexible flying machine. The types of experiments that might be supported in an ISES environment become more generalized than just Earth sciences. Experiments in controls, structures, and artificial intelligence are possibilities as well as those related to Earth observations.

Conclusions

A concept called ISES has been proposed and discussed in this paper which makes use of a new opportunity, the Eos, to evaluate the role of onboard information extraction in space flight

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systems. Onboard information extraction is a possible part of the solution to the growing "data glut problem" associated with Earth-viewing remote sensors. The ISES concept offers additional opportunities in better use of onboard instrumentation, real-time response to events, and a way to evaluate new technology in space without jeopardizing mission safety. Finally, the applicability of the ISES concept to the core station was discussed, including important differences between a possible Eos version and core station version of the ISES concept.

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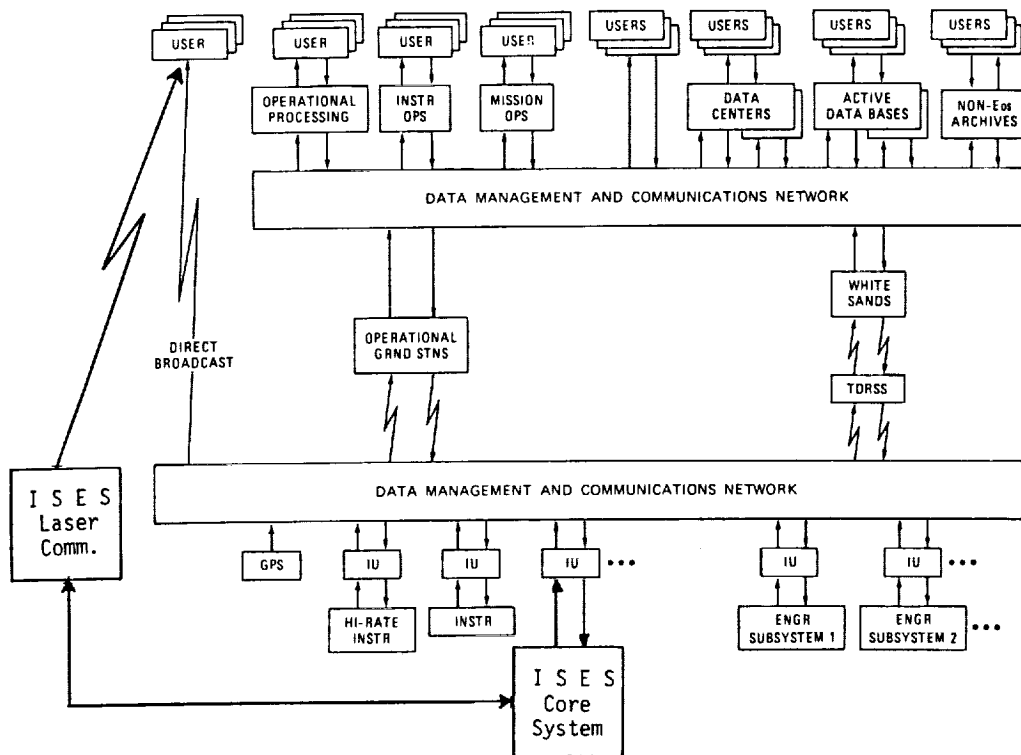


Figure 3. ISES concept integrated into Eos flight element showing eavesdropping access to real-time instrument data.

EOS INFORMATION PROCESSING ARCHITECTURE

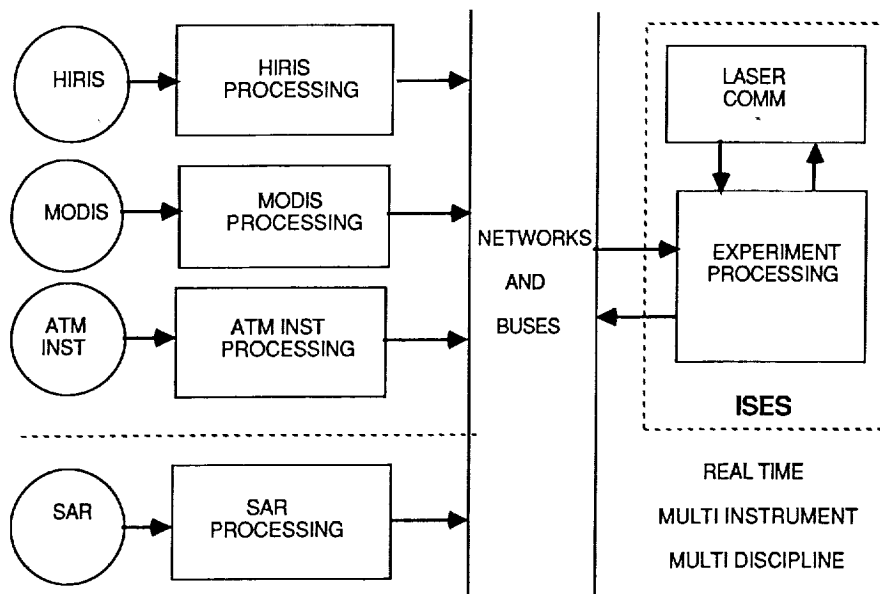


Figure 4. Relation of ISES to other onboard sensor processing such as internal-to-the-instrument data processing.

Addresses:

- Capability for direct interactive links to users
- Experiments in advanced optical communications

Access stations at poles

Optical communications data link

Features:

- Low speed bi-directional communications
- Gigabit/sec speed optical communications

The diagram illustrates a satellite communication system. At the top, a satellite is shown with a complex internal structure. Below it, a dashed line represents the 'Optical communications data link' connecting the satellite to a ground station on the Earth's surface. The ground station is depicted as a tall tower with a large parabolic dish antenna. To the left of the ground station, a small inset shows a circular cross-section of the Earth with 'N' for North and 'S' for South. Two small satellite-like icons are positioned at the North and South poles, with lines indicating their connection to the main satellite. Arrows labeled 'Control' and 'Data' point between the satellite and the ground station, indicating bidirectional communication. The Earth's surface is shown at the bottom, with some landmasses visible.

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